Sizing Hydraulic Structures in old Regions to Balance Fish Passage, Stream Function, and Operation and Maintenance Cost

Center for Environmentally Sustainable Transportation in Cold Climates

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U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

INE/CESTiCC 19.07

REPORT DOCUMENTATION PAGE

Form approved OMB No.

1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	03/31/2019	Final Report: 01/2016 – 03/2019

4. TITLE AND SUBTITLE

Sizing Hydraulic Structures in Cold Regions to Balance Fish Passage, Stream Function, and Operation and Maintenance Cost

5. FUNDING NUMBERS

6. AUTHOR(S)
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University of Alaska Fairbanks
Duckering Building, Room 245
P.O. Box 755900
Fairbanks, AK 99775-5900

8. PERFORMING ORGANIZATION REPORT NUMBER

INE/AUTC 19.07

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLENMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
No restrictions	

13. ABSTRACT (Maximum 200 words)
The purpose of this research was to evaluate how characteristics of hydraulic structures, such as slope or size, used at crossings over waterways relate to operation and maintenance (O&M) effort, fish passage, and stream function. Data on O&M concerns, fish passage concerns, and crossing characteristics were collected from 45 road-stream crossings in Prudhoe Bay, Alaska, during lower and higher water periods in both 2014 and 2015 (four events total). Logistic regression and generalized mixed models were used to examine relationships between O&M effort (response) and five explanatory variables. For all data from all years combined, there were no observable associations among O&M and culvert type or constriction ratio. However, lower constriction ratios were observed for sites with O&M needs in the June 2014 data set. The proportion of sites with both fish passage and O&M concerns was 0.52; comparatively, the proportion of sites with no fish passage concern but with O&M concern was 0.35.

14- KEYWORDS:
culverts, operation and maintenance, cost-benefit, fish passage, stream function

15. NUMBER OF PAGES
36

16. PRICE CODE
N/A

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Final Report

by

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A report prepared for the
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INE/AUTC 19.07

March 31, 2019

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
Note: Volumes greater than 1000 L shall be shown in m^3				
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2 m^2
meters squared		10.764	square feet	ft^2 km^2
kilometers squared		0.39	square miles	mi^2 ha
hectares (10,000 m^2)		2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb mg
megagrams (1000 kg)		1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

-40ºF	0	32 40	80	98.6 120	160	200 212ºF		
-40ºC	-20	0	20	37 40	60	80	100ºC	

ACKNOWLEDGMENTS

The authors would like to thank BP Exploration (Alaska), Inc. (BPXA) for contributing to this project. Specifically, Bill Streever, who is now retired, and Christina Pohl for their support of this research effort. We would also like to thank ERM for providing data collection at project sites during 2014 and 2015.

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EXECUTIVE SUMMARY

Traditionally, federal, state and local governments, as well as private entities, install the smallest hydraulic structure able to pass a design flow as required by federal, state and/or local regulations. This traditional approach means structures are sized for water conveyance only, and often results in the use of culverts as the preferred hydraulic structure because they are efficient at passing water underneath roadways and are economical. Alternatively, structures that are sized to (1) bankfull width or larger to accommodate aquatic and wildlife passage, and/or (2) account for geomorphic processes such as the transport of large woody debris or ice, and/or (3) allow for uncertainty about estimates of hydrologic design flows due to changing climates, are usually larger and may be designed and constructed in a different manner. The purpose of this research was to evaluate how characteristics of hydraulic structures, such as slope or size, used at crossings over waterways relate to operation and maintenance (O&M) effort, fish passage, and stream function.

Data on O&M concerns, fish passage concerns, and crossing characteristics (i.e., culvert type, slope, and constriction ratios) were collected from a total of 45 sites in three operating areas (East, West, and North) on the BPXA (British Petroleum Exploration Alaska, Inc.) lease of Prudhoe Bay, Alaska. Logistic regression and generalized linear mixed models were used to examine relationships among O&M concerns (response variable) and five explanatory variables: fish passage concerns, culvert type, culvert slope, constriction ratio, and flooding from a 2015 flood event.

Key results and conclusions include:

- There were no observable associations among O&M concerns and culvert type or constriction ratio ($P>0.1$) for pooled data (all years combined).

- Lower constriction ratios were observed for sites with O&M needs in the June 2014 data set.
- Operation and maintenance concerns were associated with the 2015 flood event and fish passage concerns.
- The proportion of sites with both fish passage and O&M concerns was 0.52; comparatively, the proportion of sites with no fish passage concern but with O&M concern was 0.35.

There are a few recommendations that stem from this work:

- Crossings with low constriction ratios were associated with O&M concerns for one sampling period; therefore, data suggest that designs sized larger, and thus having a higher constriction ratio, may require less O&M effort.
- The result that O&M, fish passage concern, and stream degradation shared some criteria suggests that these concerns may be related. This result also suggests that larger crossings, such as those sized to match the stream channel width, may require less O&M, and may be less likely to impede fish passage and degrade stream channels.

CHAPTER 1. INTRODUCTION

Traditionally, federal, state and local governments, as well as private entities, install the smallest hydraulic structure able to pass a design flow as required by federal, state and/or local regulations. This traditional approach means that structures are sized for water conveyance only, and often results in the use of culverts as the preferred hydraulic structure because they are efficient at passing water underneath roadways and are economical. Alternatively, structures that are sized to (1) bankfull width or larger to accommodate aquatic and wildlife passage, and/or (2) account for geomorphic processes such as the transport of large woody debris or ice, and/or (3) allow for uncertainty about estimates of hydrologic design flows due to changing climates, are usually larger and may be designed and constructed in a different manner.

Larger structures usually mean higher initial cost investment; however, one of the perceived benefits of these larger structures is that long-term operation and maintenance (O&M) costs would be less because the structure allows for natural stream functions such as the unrestricted passage of flows up to the structures' width, and unimpeded woody debris (if present in the watershed) and sediment transport. Comparatively, smaller structures that are designed only to pass a design flow may create channel aggradation upstream of the crossing, cause debris jams, and create excessive scour on the downstream end of the crossing—factors that could result in higher risk of hydraulic failure, reduced structure life, increased O&M effort and the probability of expensive retrofits, and increased potential of creating a barrier to the mobility of aquatic organisms.

The expected increased frequency of intense storms in many areas of the nation implies that existing stream crossings will become even more costly, since they will require yet more O&M and replacement. During major storms, smaller crossings fill with water, clog with debris, and worsen flood impacts. Over time, water passing through smaller designed culverts can scour away the surrounding soil and increases the likelihood of sudden failure during large storms, whereas properly sized and designed crossings can withstand these storms without major damage. Improved crossings can therefore help avoid expensive unplanned repairs to infrastructure resulting from both flooding and stream crossing failure.

The problem is that there has not been a thorough analysis of the range of structures available for crossings that require fish passage, or larger sizes for geomorphic reasons, and notably with respect to the secondary benefits they may offer (such as increased resilience to climate change) as outlined above. Therefore, departments of transportation and other entities with large road systems and culvert crossings do not have sufficient information to make effective decisions as to what design should be used in order to balance the initial monetary expenditure to construct or re-construct crossings with the continued O&M effort, and the ecological needs of the stream or river system.

The purpose of this research was to evaluate how characteristics of hydraulic structures, such as slope, size, or constriction ratio, used at crossings over waterways relate to O&M effort, fish passage, and stream function. This effort will better inform future road-stream crossing designs, with the goal of achieving cost-effective designs that provide proper fish and other aquatic organism passage, stream function, and resilience to changing climates without excessive initial investment.

1.1 Background

Where roads intersect water bodies such as streams and rivers, a hydraulic structure is used to pass water underneath the road. There are many different types and sizes of hydraulic structures available to a design team, and typically they are grouped into either bridges or culverts. Selection of an appropriate structure or structures at a crossing includes evaluation of many different factors, with a few of the more important being the design flood flow, the morphology of the water body being crossed, the aquatic species in the stream system, the traffic demands for the road, and, of course, cost.

Improperly designed, constructed or maintained culverts can impede or prevent fish passage and severely impair stream function [1]. The most common factors that create barriers to fish passage are insufficient water depth, large outlet drop, excessive water velocity, and debris jams [2, 3, 4, 5, 6, 7, 8, 9]. Sixty-one percent of culvert crossings in the Notikewin watershed and 74% of culvert crossings in the Swan River watershed, both in Alberta, likely impede fish movement [10]. A study designed to assess culvert barriers to fish movement along the Trans Labrador Highway found that 22 of 47 culverts (47%) probably allowed passage of all size classes of fish and that 25 of 47 culverts (53%) were barriers [1]. In Montana, the U.S. Forest Service (USFS) had catalogued over 1,500 culverts at fish-bearing streams on National Forest lands. Of these, 47% were classified as barriers and 15% as passable; 38% are unclassified [11]. Studies of culvert barriers in the Great Lakes identified 19% of culverts as barriers [12].

Stream-simulation designs for new crossings mimic natural channel characteristics through the road-stream crossing and have proven effective at providing fish passage and maintaining river function. Stream-simulation culverts can be designed and constructed using a variety of different culvert types and shapes including round, bottomless arches, box, and squash (or elliptical) shapes amongst others [13, 14]. In addition, these designs can utilize single or multiple structures. Multiple structure designs typically use a primary structure for the main channel and additional structures to convey higher flows that activate side-channels or floodplain areas. Hydraulic Engineering Circular (HEC) No. 26, Culvert Design for Aquatic Organism

Passage, is one of many recent design guidelines that summarize the range of methods for designing new crossings that require aquatic passage [15].

The effects of "stream simulation" on aquatic species movement, habitat and channel form have been investigated recently. In Alaska, crossings on a salmon stream in Anchorage were replaced with new crossings designed to mimic natural channel conditions. The study used a pre-post monitoring design to evaluate the response of salmon in the system to the new crossings. Monitoring showed a 300% increase in coho salmon escapement from pre- to post-restoration, from 481 adults in 2008 to approximately 1500 adults a year on average between 2009 to 2013 [16]. A study in Washington State evaluated 50 culverts designed following stream-simulation approaches by comparing channel bed and hydraulic conditions between culvert (treatment) reaches and reference reaches. The study found that sediment size and gradation, velocity at the 2-year recurrence interval (RI) flow, and flow widths (width of water at surface) during the 2-year RI flow were similar between culvert and control reaches. Culvert reaches, however, were not as likely to maintain channel complexity, because it is difficult to accommodate natural channel-forming features from woody debris or vegetative processes within them. The study also found that stream simulation culverts did not deteriorate from large flood events observed, which implies that this approach maintains flood resiliency [14].

One common prediction of climate change is the increase in low-frequency (high precipitation amounts) storms [17]. Changes in precipitation amounts are predicted to occur more in some environments than in others, with some of the greatest changes occurring in sub-Arctic to Arctic regions. Designing larger spans to better accommodate stream and floodplain function as well as fish and wildlife passage also makes the crossing more resilient to future large flood events. Additionally, increasing habitat connectivity has been identified as one of the most promising mitigation techniques for aquatic species threatened by changing climates [18].

Road crossing design requires estimation of a flood flow to determine size of crossing structures and road surface elevations amongst other road features. In the United States, the design flood flow for most county roads is the 50-year recurrence interval (RI) flood. This value is typically determined based on empirical data from the past climate record, using either records of gaged data or regional regression equations. With changing climates affecting future flood size and frequency, many countries have already begun to change their design flood RI, or their road design practices, based on how the future climate may look versus relying upon past climate records. For example, the Norwegian Public Roads Administration is requiring that the design elevation for road surfaces be based on a 200-year RI. The Danish Road Directorate has made a practice of planning new roads away from locations that have a high risk of flooding [19].

Cost-benefit studies evaluating how culverts designed following stream-simulation techniques as compared with traditional methods have recently been completed. A study in Wisconsin evaluated 495 culverts and quantified the fiscal and social costs and benefits of replacing culverts designed following traditional methods with those designed following a stream-simulation technique [20]. Researchers calculated an average net fiscal benefit of -$4,500 and an average net social benefit of $7,800 for those designed following a stream-simulation technique. The data also showed 44% of the study culverts following stream-simulation techniques had net fiscal benefits and 77% had net social benefits. The authors found that culverts which showed measurable environmental damages such as downstream scour resulted in the largest net benefits from replacement with a stream-simulation design.

1.2 Objectives

For this research, we attempted to answer the following question: Do larger crossings that better accommodate stream function and provide unimpeded fish passage, require less O&M effort than smaller crossings sized to less than the stream bankfull width? This question is directly tied to another one: Is there a relationship between O&M concerns and fish passage? To address this question, we evaluated relationships between structure size, stream channel function, fish passage impedance, and O&M effort.

CHAPTER 2. METHODOLOGY

2.1 Data Collection

Data on operations and maintenance (O&M) concerns, fish passage concerns, and crossing characteristics (culvert type, slope, and constriction ratios) were collected from a total of 45 sites in three operating areas (East, West, and North) on the BPXA lease of Prudhoe Bay, Alaska. Figure 2.1 shows the location of Prudhoe Bay.

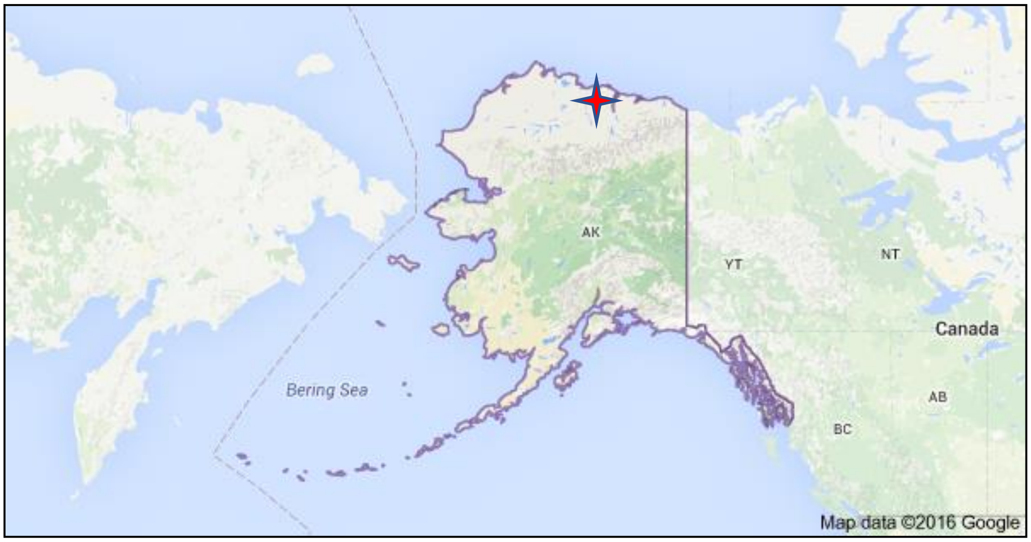

Figure 2.1 Culvert sites located in Prudhoe Bay (star), Alaska

Data were collected twice a year during typical high flow (June) and low flow (September) periods in 2014 and 2015. Data were not collected from all sites for every collection period, and data from the North Operating Area (n=11 sites) were only collected for the two 2014 collection periods. No data collection was possible at these 11 sites after 2014 due to changes in ownership. Figure 2.2 shows examples of two crossings: one a medium-sized crossing and a second larger crossing.

Figure 2.2 Photographs of culvert sites in Prudhoe Bay, Alaska

Physical data describing culvert and road characteristics, hydraulic conditions, stream channel conditions, and evidence of existing failure mechanisms were quantified. Operation and maintenance concerns were identified based on the presence and severity of existing failure mechanisms. Briefly, data collection included the following:

Culvert and road characteristics were measured including culvert size (i.e., width, span, rise, etc.), slope of culvert, number of culverts, culvert type (i.e., corrugated metal pipe, smooth steel, etc.), length, and inlet and outlet configuration. The measurements were collected using engineering tapes, survey levels, and engineering stadia rods.

Hydraulic conditions included measurement of the following:

- Water depth, collected at the culvert inlet and outlet. Multiple measurements across the inlet and outlet of the culvert were collected in larger culverts (those greater than 3 ft in diameter or span). Water depth was collected with a graduated rod to the nearest +/- 0.05 ft.
- Water velocity at 0.6 times the water depth, collected at the culvert inlet and outlet. This location represented the average velocity in that portion of the culvert. Water velocity coincided with each water depth location; therefore, there were multiple

velocity measurements in larger culverts. Water velocity was collected with a Marsh McBirney Flo-Mate recorder.

- Outlet drop height, measured at each crossing. This measurement was taken as the vertical distance between the water surface elevation at the culvert outlet and the water surface elevation in the plunge pool adjacent to the culvert outlet. Water depth was collected with a graduated rod to the nearest +/- 0.05 ft.
- Evidence of debris or other blockage, measured at each crossing. This measurement was taken visually and grouped as either no blockage, minor blockage or obvious blockage.

Stream channel width measurements were collected at all crossing locations, if possible. Measurements of bankfull channel width and the width of the stream at ordinary high water were collected. We attempted to collect measurements outside the influence of anthropogenic features, such as the culverts, to attempt to characterize natural channel conditions. Channel widths in riffle areas were typically measured (where possible), as those areas are more representative of channel-forming processes; in addition, locations where one might elect to span a stream or river with a road-stream crossing.

Fish passage impedance was initially ranked as one of three possible categories: (1) no concern, (2) potential concern, or (3) concern likely based on physical thresholds set relative to the hydraulic data collected at each crossing. A no-concern ranking indicated very little possibility for fish passage impedance; a potential-concern ranking indicated some possibility for fish passage impedance; a concern-likely ranking indicated high possibility for fish passage impedance. The physical thresholds were based on a review of fish passage literature, Alaska Department of Fish and Game recommendations for passage of Arctic grayling, and professional experience of the project team. Grayling were the fish species used to set the thresholds (Table 2.1).

Table 2.1 Thresholds for ranking fish passage impedance based on swimming abilities of Arctic grayling

Factor	Threshold	Ranking
Outlet Drop	no outlet drop	no concern
	outlet drop up to 0.25 ft (3 inches)	potential concern
	outlet drop greater than 0.25 ft (3 inches)	concern likely
Minimum Water Depth	water depth greater than 0.7 ft	no concern
	water depth between 0.3 and 0.7 ft	potential concern
	water depth less than 0.3 ft	concern likely
Water Velocity	water velocity less than 3.0 ft/s	no concern
	water velocity between 3.0 ft/s and 5.0 ft/s	potential concern
	water velocity greater than 5.0 ft/s	concern likely
Debris or Other Blockage	no blockage	no concern
	minor blockage	potential concern
	obvious blockage	concern likely

The constriction ratio (CR) was calculated at each road-stream crossing, unless the waterbody was not a stream or river. Some of the road-stream crossings in this dataset were lake-to-lake connections or wetland connections; therefore, CR was not collected in these settings. The CR was the culvert width divided by the average channel width at ordinary high water (OHW). Larger CRs represented structures that accommodate stream function better.

Evidence of existing failure mechanisms was described qualitatively and used to rank the O&M effort at each crossing. Data collection included qualitative measurements of structural damage to culvert inlets or outlets, road embankment failure, excessive and unnatural sedimentation, and excessive sediment deposition in the culvert. These observations were categorized into one of three categories: low or no concern for O&M, medium concern for O&M, and high concern for O&M.

Due to the small sample size, the initial three-part risk categorization (no concern, potential concern, and concern likely) for O&M and fish passage concerns was reduced to a simpler binary risk categorization (concern, no concern). Thus, potential concern and concern likely were not differentiated, and both led to a concern rating in the binary risk categorization. Operation and maintenance concerns were further refined and based only on the assessment of sediment in the channel/culvert and road embankment. The physical condition of the culvert was not used to categorize O&M concern due to physical damage resulting primarily from snow and ice removal. Similarly, structural issues impeding passage were not used to categorize fish passage concerns (Note: This did not change any concern categorizations in the data set used for analysis).

Fish passage concerns were based on assessment of inlet and outlet depth, excessive water velocity, outlet drop, and debris or sediment impedance of passage as previously described. Sites with multiple culverts were given a no-concern rating for fish passage if *at least one* of the culverts did not have any concerns in the aforementioned categories. Sites were given a stream-degradation characterization based on sediment in the channel, road embankment scour, and debris or sediment inhibiting passage. A large flood in 2015, prior to both data collections for that year, affected many sites and warranted an additional binary variable (Yes/No) to indicate if the site was affected by the flood.

The original data set was reduced for analysis to only include sites that were evaluated for O&M concerns, fish passage concerns, and culvert characteristics (culvert type, slope, and constriction ratio). The sites that represented corridors between lakes and had no discernable constriction ratio were dropped from the data set as previously described. See Table 2.2 for a description of the full and reduced data sets.

Table 2.2 Sample size for each collection period

Collection Period	Full Sample Size	Reduced Sample Size	Reasons for Reduced Sample Size
June 2014	45	22	23 sites without constriction ratios, of these 5 also did not have fish passage or O&M characterization
September 2014	45	18	23 sites without constriction ratios, 5 without fish passage characterization due to a lack of water (one of these also did not have a constriction ratio)
June 2015	34	16	14 sites without constriction ratios, 4 without fish passage characterization due to a lack of water (one of these also did not have a constriction ratio), 1 without sediment in channel recorded
September 2015	34	17	14 sites without constriction ratios, 4 without fish passage characterization due to a lack of water (one of these also doesn't have a constriction ratio)

Note: Full sample size between 2014 (n = 45) and 2015 (n = 34) was reduced due to ownership changes.

2.2 Data Analysis

Logistic regression and generalized linear mixed models were used to examine relationships among O&M concerns (response variable) and 6 explanatory variables: fish passage concerns, culvert type, culvert slope, constriction ratio, flow (high/low), and flooding from a 2015 flood event. Operation and maintenance, fish passage concerns, and flooding were discrete binary variables, culvert type was a discrete variable with 4 levels (SS, CMP, CMP/SS, SSP), and culvert slope and constriction ratio were treated as continuous variables. A small sample size, temporal and spatial dependence of observations, and some sites not being evaluated for every category during every observation period presented difficulties to data analysis. Because an analysis method to account for all these concerns was not available, a number of analysis techniques were applied to the data that accounted for these concerns to differing degrees.

Data from each of the four collection periods were analyzed separately using logistic regression in order to allow analysis of all the data while eliminating concerns of the spatial and temporal dependence of observations. An Akaike information criterion corrected for small sample size (AICc) model selection was used to choose the best fitting model from the model set including all combinations of the explanatory variables culvert type, culvert slope, flooding, and constriction ratio. Flow (high/low) was not included in the variable set because it did not differ within a collection period. Model fit was assessed using a log-likelihood test, comparing the selected model and the model with only an intercept. Interactions were not included due to the small sample size and discrete variables not being crossed (i.e., every level of a discrete variable does not occur with every level of the other discrete variables). Because the question of interest was to evaluate if there was an association between O&M concerns and fish passage concerns, fish passage was not included in the initial model set, but was added to the selected model. Assumptions of linearity and normality were examined by plotting continuous variables (culvert slope and constriction ratios) against empirical logits and boxplots, respectively. Assumptions appeared to be adequately met. Plots of deviance residuals vs. explanatory variables and fitted values were used for model validation and identification of trends not accounted for in the model.

To maximize the sample size examined, logistic regression was also performed using data pooled from all evaluations and assuming independence of evaluations. Analysis of deviance tests were used to assess single term deletions of explanatory variables. The least significant explanatory variable was deleted, the model was refit, and the drop-in deviance test was used to evaluate the significance of remaining variables. The process was repeated until only significant variables remained in the model.

Generalized linear mixed models were used in order to increase the sample size, pool data from the four collection periods, and account for dependence of observations from the same site. Fish passage, culvert type, culvert slope, flooding, flow, and constriction ratios were fixed effects, and a random intercept for "Crossing Identity" was added. Random intercept mixed models assume a compound symmetrical correlation structure, which implies that the probability of an observation having O&M concerns is correlated to other observations for the same crossing site. Only sites with data for all four collection periods were included in the data set. The logistic link function was used to model O&M concerns as a binary response variable. Because AICc model selection techniques are not accurate with mixed-effects models, due to each parameter having both fixed and random components, a backward stepwise selection process was used. In this process, the full model with all explanatory variables was fitted first, and the variable with the least statistical support, based on *p*-values from Wald's *Z*-statistics, was dropped to form a reduced model. Likelihood ratio tests based on maximum likelihood estimators were used to compare models, and variables were dropped when $P>0.10$. This process was repeated until a final model was selected. Parameters from the final model were estimated using restricted maximum likelihood estimation [21]. Fish passage was retained in all models in order to examine the primary question of interest: Is there a relationship between O&M concerns and fish passage?

Logistic regression on the counts of binomial responses (i.e., binomial regression) for each site was conducted to examine the site-specific frequency of O&M concerns. The response variable was the proportion of evaluations for a given site that had O&M concerns. Explanatory variables included fish passage concerns, culvert type, culvert slope, crossing type, and flooding. Due to how the data were grouped by site, fish passage concerns and flooding were treated as a continuous proportion of the number of evaluations for a given site that had fish passage concerns or flooding. Additionally, due to the structure of the data, flow (high/low) was not included in the variable set. Quasi-likelihood estimation was used to account for extra-binomial variation, which likely arose from a lack of independence of the binary responses that made up the binomial count. Scatterplots of the empirical logits versus continuous explanatory variables were made to evaluate linearity or higher order relationships. Pearson's residuals were examined to identify potential outliers and trends between residuals and explanatory variables. A goodness-of-fit test on the model with all covariates was used to assess model fit. The methods used for model selection are the same as those used for the logistic regression on the binary response, except that a normal distribution for the variables was not assumed and a *t*-distribution was used instead of a *z*-distribution.

All data analysis was conducted in program R, version 3.3.1 [22]. The *lme4* package [23] and *glm* function [22] were used to fit generalized linear models.

CHAPTER 3. RESULTS

Because the data were analyzed using multiple statistical models, the results vary depending on which model was used, and in some cases, the results may seem contradictory from one model to another. The results, however, are tied to the model used and the assumptions behind it. Part of the reason for this is the different ways of accounting for lack of independence of observations for each method and differing sample sizes. Different methods were used to account for lack of spatial (e.g., different sites) and temporal (e.g., different time periods) independence.

A total of 73 evaluations taken at 22 crossing sites had complete records of O&M concerns, fish passage concerns, and culvert characteristics (culvert type, slope, and constriction ratio). Of these evaluations, O&M and fish passage concerns were observed together 15 times, neither were observed 29 times, and one was observed without the other 29 times. The proportion of sites with fish passage concerns that had O&M concerns was 0.52, whereas the proportion of sites without fish passage concerns that had O&M concerns was 0.35. Ignoring potential associations among O&M, culvert slope and type, flooding, and constriction ratio, there was no evidence for the odds of having O&M concerns differing between sites with and without fish passage concerns (Z-stat=1.35, P=0.18). There were also no observable associations among O&M concerns, fish passage concerns, culvert slope, and constriction ratio (Figure 3.1, 3.2). The difference between these two figures is that Figure 3.1 shows plots of observations with/without O&M concerns, and Figure 3.2 shows plots of observations with/without fish passage concerns.

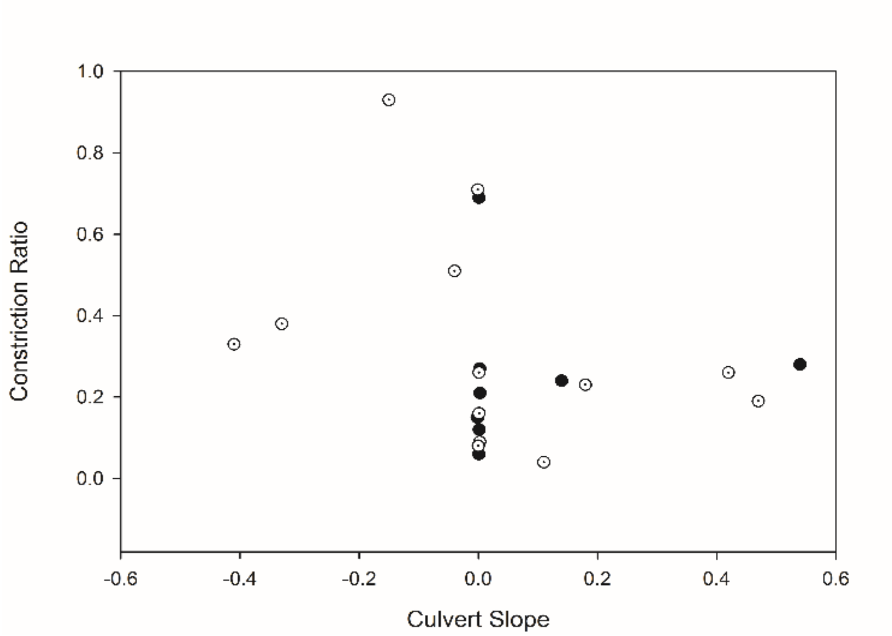

Figure 3.1 Coded scatterplot of constriction ratio versus culvert slope.
(filled circles represent observations *without O&M concerns*; open circles represent observations with O&M concerns)

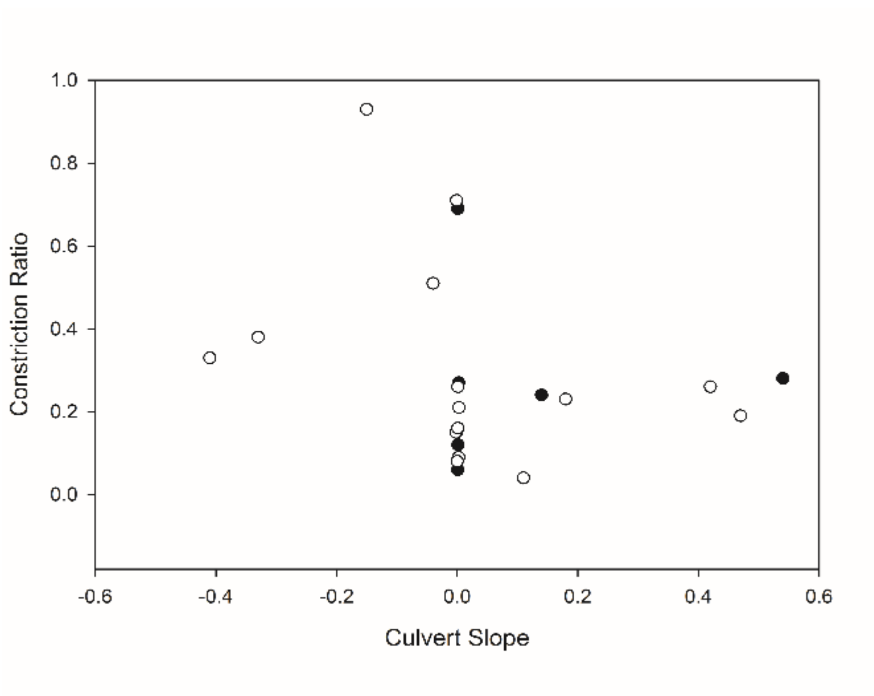

Figure 3.2 Coded scatterplot of constriction ratio versus culvert slope.
(filled circles represent observations *without fish passage concerns*, open circles represent observations with fish passage concerns)

All sites with O&M concerns also had stream degradation concerns. See Table 3.1 for a summary of sites with O&M concerns. Fish passage concerns were most common in the June 2014 collection, with 18 of 22 sites having fish passage impedance concerns. In both June and September 2015, fish passage concerns were observed only at 5 sites, and for the September 2014 evaluations, fish passage concerns were observed at 6 sites. Operation and maintenance concerns were generally more common in the 2015 collections than in the 2014 collections, and more common at low-flow evaluations (September) than at high-flow evaluations (June) (Table 3.1).

For the June 2014 evaluations, 3 sites had O&M concerns, and all 3 also had fish passage concerns. Ten sites had fish passage concerns without O&M concerns. Mean constriction ratio was lower for sites with O&M concerns (0.12, SD=0.06) than for sites without O&M concerns (0.31, SD=0.23; Table 3.1). No noticeable trends were observed among O&M, culvert type, or culvert slope. The log-odds of having O&M concerns was modeled as a linear combination of the constriction ratio and passage concern in the model with the lowest AICc value (13.5). There was limited evidence (Wald's *Z*-Stat= -1.41; *P*=0.16) for a negative relationship between constriction ratio and the log-odds of having O&M concerns. There was no evidence for a relationship between fish passage concerns and O&M concerns (Wald's *Z*-stat=0.005; *P*=0.996). The selected model did not fit significantly better than the intercept-only model ($\chi 2$ =10.1, d.f.=2, *P*=0.99).

For the September 2014 evaluations, 8 sites had O&M concerns; of these, 5 also had fish passage concerns. One additional site had fish passage concerns without O&M concerns. No noticeable trends were observed among O&M, constriction ratio, culvert type, or culvert slope. The log-odds of having O&M concerns was modeled as a linear combination of the constriction ratio, culvert slope, and fish passage concerns in the model with the lowest AICc value (8.0). There was no evidence of relationships among O&M concerns, constriction ratio, culvert slope, or fish passage concerns (*P*=1). The selected model did not fit significantly better than the intercept-only model ($\chi 2$ =7.7, d.f.=3, *P*=0.94).

Table 3.1 Summary of sites with O&M concerns for all data sets combined.

Collection Period	Total Sample Size	Number of Sites with O&M Needs	Number of Sites with Fish Passage Impedance[1, 2]	Mean Slope[2]	Mean Constriction Ratio[2]	Culvert Type[2]
June 2014	22	3	3 (18; p=9, c=9)	0.158 (0.043)	0.120 (0.288)	CMP: 1 (8) CMP/SS: 1 (3) SS: 1 (7) SSP: 0 (4)
September 2014	18	8	5 (6; p=5, c=1)	0.025 (0.0521)	0.346 (0.316)	CMP: 2 (4) CMP/SS: 2 (3) SS: 2 (7) SSP: 2 (4)
June 2015	16	9 (p=5, c=4)	4 (5; p=4, c=1)	0.049 (0.048)	0.288 (0.273)	CMP: 4 (5) CMP/SS: 1 (3) SS: 2 (5) SSP: 2 (3)
September 2015	17	10 (p=3, c=7)	3 (5; p=3, c=2)	0.011 (0.037)	0.327 (0.312)	CMP: 4 (5) CMP/SS: 2 (3) SS: 1 (5) SSP: 3 (4)

Table notes:
[1.] p – Potential concern for fish passage impedance; c – concern likely for fish passage impedance.
[2.] Values for characteristics of sites *with* O&M concerns presented first, with the total number from the data set (i.e., observations with and without O&M concerns) presented in parentheses.

For the June 2015 evaluations, 9 sites had O&M concerns; of these, 4 also had fish passage concerns. One additional site had fish passage concerns without O&M concerns. Seven of the 9 sites with O&M concerns were affected by the 2015 flood. No noticeable trends were observed among O&M, constriction ratio, culvert type, or culvert slope. The log-odds of having O&M concerns was modeled as a linear combination of constriction ratio, culvert type, and fish passage concerns in the model with the lowest AICc value (12.0). There was no evidence for relationships among O&M concerns, constriction ratio, culvert type, or fish passage concerns (P=1). There was limited evidence that the selected model fit significantly better than the intercept-only model ($\chi 2$ =1.8, d.f.=5, P=0.12).

For the September 2015 evaluations, 10 sites had O&M concerns; of these, 3 had fish passage concerns. Two additional sites had fish passage concerns without O&M concerns. No noticeable trends were observed among O&M, culvert type, constriction ratio, or culvert slope. The log-odds of having O&M concerns was modeled as a function of fish passage concern in the model with the lowest AICc value (26.0; i.e., the intercept-only model was selected during the model selection process). There was no evidence for relationships among O&M concerns and fish passage concerns (Wald's Z-stat=-1.0; P=0.32). There was no evidence that the selected model fit significantly better than the intercept-only model ($\chi 2$ =1.0, d.f.=1, P=0.69).

When data were pooled and independence of evaluations was assumed, 73 evaluations were included in the data set used for logistic regression. Culvert slope ($\chi 2$=0.01, P=0.91), culvert type ($\chi 2$=2.24, P=0.52), and constriction ratio ($\chi 2$=0.09, P=0.76) were not significant and were removed from the inferential model. Flood occurrence was significantly associated with O&M concerns (Wald's Z-stat=3.61, P=0.0003), and the odds of having O&M concerns for flood-affected sites were 16.9 times the odds of having O&M concerns for non-flood-affected sites (95% CI: 4.2 times to 95.6 times). There was moderate evidence that fish passage concerns were associated with O&M concerns (Wald's Z-stat=2.2, P=0.03), and the odds of having O&M concerns were 2.9 times greater for sites with fish passage issues than for those without fish passage issues (95% CI=1.2 times to 14.7 times). There was moderate evidence that flow (high/low) was associated with O&M concerns (Wald's Z-stat=2.1, P=0.04), and the odds of having O&M concerns were 3.53 times greater for sites evaluated at low flow than at high flow (95% CI= 1.1 times to 12.5 times).

Of the 22 sites evaluated, 15 were evaluated during all 4 collection periods and were included in the data set used for generalized mixed modeling. Of these sites, 7 were affected by a flood prior to the 2015 collections. All of these sites were characterized as having an O&M concern for at least 1 of the 2015 evaluations, and 11 of the 14 evaluations with O&M concerns were from flood-affected sites. Generalized mixed-effects modeling indicated no evidence for relationships between constriction ratio ($\chi2$ =0.0004, d.f.=1, P=0.98), culvert slope ($\chi2$ =0.04, d.f.=1, P=0.83), culvert type ($\chi2$ =1.4, d.f.=3, P=0.69), flow ($\chi2$ =2.8, d.f.=1, P=0.10), and O&M concerns, and these variables were removed from the inferential model. The inferential model included only terms for flooding and fish passage concerns. There was no evidence for a relationship between O&M and fish passage concerns (Wald's Z-stat=-0.072, P=0.94). However, there was evidence for a relationship between flooding and O&M concerns (Wald's Z-stat=-2.528, P=0.01). Being affected by a large flood was predicted to increase the odds of having O&M concerns by 65.4 times the odds of having O&M concerns for sites not affected by a flood (95% CI: 5.4 times to 2,251.6 times).

The logistic regression model on the binomial counts (O&M concern vs. no O&M concern) for each site (n=22) indicated that O&M concerns were associated with flooding and fish passage. A goodness-of-fit test indicated that the model was inadequate in describing the response distribution. However, due to the small number of counts for each site, this test can give misleading results. Additionally, the lack of fit is assumed to be caused by extra-binomial variation, likely resulting from a lack of independence of the binary responses making up the binomial count. This was corrected for using quasi-likelihood estimation with a dispersion parameter of 1.7. There was no evidence that O&M concerns were related to culvert slope ($\chi2$=0.0004, P=0.98), culvert type ($\chi2$=1.75, P=0.63), or constriction ratio ($\chi2$=0.02, P=0.89). There was suggestive evidence that O&M concerns were associated with fish passage concerns (t-stat= 2.1, P=0.05), and the odds of having O&M concerns increased by a factor of 2.9 (95% CI: 1.1 times to 8.1 times) with an associated 50% increase in fish passage concerns. There was convincing evidence that O&M concerns were associated with flooding (t-stat=3.3, P=0.002), and the odds of having O&M concerns increased by a factor of 3.8 (95% CI: 1.6 times to 15.3 times) with an associated 50% increase in the risk of flooding.

CHAPTER 4. CONCLUSIONS

That statistical analysis did not reveal consistent relationships among O&M concerns, fish passage concerns, culvert type, culvert slope, and constriction ratio does not mean these variables are not associated. Lower constriction ratios were observed at sites with O&M needs for the June 2014 evaluations. Overall, 52% of sites analyzed in the data set that had O&M concerns also had fish passage concerns compared with 35% of sites having O&M concerns but not having fish passage concerns. All sites that had O&M concerns also had stream degradation concerns. The fact that O&M, fish passage concerns, and stream degradation concerns shared some identification criteria (i.e., sediment in the channel, road embankment, debris, or sediment blocking culvert) suggests a relationship between these concerns. However, analysis was unable to determine statistically significant trends due to a small sample size relative to the number of factors.

Analysis indicated that sites shared similar O&M and fish passage evaluations throughout evaluations/time regardless of their culvert characteristics. In the mixed-effects models, the correlation among evaluations from the same sites was so great that it obscured any relationships between O&M and fish passage concerns. However, binomial regression, which assessed the frequency of O&M and fish passage concerns at a given site, suggested that sites with a high frequency of O&M concerns also had a high frequency of fish passage concerns.

CHAPTER 5. RECOMMENDATIONS

Key results and conclusions are summarized here:

- There were no observable associations among O&M concerns and culvert type or constriction ratio (*P*>0.1) for pooled data.
- Lower constriction ratios were observed for sites with O&M needs in the June 2014 data set.
- Operation and maintenance concerns were associated with the 2015 flood event and fish passage concerns.
- The proportion of sites with both fish passage and O&M concerns was 0.52; comparatively, the proportion of sites with no fish passage concern but with O&M concern was 0.35.
- All sites in the reduced data set with O&M concerns also had stream degradation concerns

A few recommendations stem from this work:

Crossings with low constriction ratios were associated with O&M concerns for one sampling period; therefore, this data suggest that designs sized larger, and thus having a higher constriction ratio, may require less O&M effort.

The result that O&M, fish passage concern, and stream degradation shared some criteria suggests that these concerns may be related. This result also suggests that larger crossings, such as those sized to match the stream channel width, may require less O&M and may be less likely to impede fish passage and degrade stream channels.

Future work in this area should focus on capturing the actual O&M cost for each crossing and compare that with measures of fish passage impedance (such as constriction ratio) and stream channel degradation.

This study had a relatively small sample size. For this reason, a few observations that did not follow the general trend had a large effect on the results. However, we studied all crossings within the jurisdiction of our research partner. We recommend increasing the sample size to provide more statistical power to further evaluate relationships between O&M, culvert sizing, fish passage, and channel degradation. An estimated 60–180 observations would be needed for models including fish passage concerns, culvert type (4 levels), constriction ratio, and culvert slope. Site evaluations for all collection periods facilitate the use of mixed-effects modeling, which allows all data to be pooled. For mixed-effects modeling, the number of sites is more important than the number of evaluations at each site. Having just two evaluations per site (high-flow and low-flow periods) may be sufficient if the number of sites evaluated is greatly increased (>50).

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